PB82-127929

Measuring the Dynamic Performance of Wind Vanes

(U.S.) Environmental Monitoring Systems Lab.
Research Triangle Park, NC

28 Jan 81

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/J-81-340
Journal Article
PB82-127929

Reprinted from JOURNAL OF APPLIED METEOROLOGY, Vol. 20, No. 5, May 1981
American Meteorological Society
Printed in U. S. A.

Measuring the Dynamic Performance of Wind Vanes

PETER L. FINKELSTEIN[1]

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

Measuring the Dynamic Performance of Wind Vanes

PETER L. FINKELSTEIN[1]

Data Management and Analysis Division, Environmental Monitoring Systems Laboratory, EPA, Research Triangle Park, NC 27711

(Manuscript received 31 October 1980, in final form 28 January 1981)

ABSTRACT

The American Society for Testing and Materials (ASTM) has proposed a standard method for testing the performance characteristics of a wind vane. This paper presents the procedures used to test and evaluate the ASTM method, and the results of that evaluation. Twelve wind vanes were borrowed from manufacturers and tested using the ASTM procedures. The starting threshold, starting accuracy, delay distance, overshoot ratio and damped wavelength were measured. Damping ratio and natural wavelength were computed from the measurements. Based on the results of these tests, it is concluded that the ASTM method provides a reasonable and reliable technique for determining performance characteristics for many types of wind vanes.

1. Introduction

Meteorological data are being used with increasing frequency in various models and site studies to help develop answers to complex environmental problems. As the decisions based on these models grow in impact and importance, the requirement for accurate input data has become more demanding. To meet this need, and to produce data of high quality, it is recognized that a quality assurance program is essential.

One part of any quality assurance program must be the determination of whether or not new and used instruments meet manufacturers and/or users performance specifications. For meteorological instrumentation this area has always been difficult, in part because there are no widely agreed upon testing procedures for determining these performance characteristics. Thus, while manufacturers may state in their literature certain properties of their instruments, or state that they will meet particular users specifications, there is usually neither information available on how the manufacturer determined the specifications of these instruments, nor a uniform way the users can determine if instruments they purchase or are using will meet their requirements.

The American Society for Testing and Materials (ASTM) has started to address this problem. They have published a standard for measuring pressure and are developing standards for measuring humidity and wind velocity. ASTM is also developing a standard method to test the dynamic performance of a wind vane,[2] and it is this method that is the subject of this study.

The proposed ASTM standard method involves a specific detailed procedure for determining the "starting threshold," "delay distance," and "overshoot" of a vane in a wind tunnel. These values are determined by recording the response of a vane after release from an initial displacement and analyzing the response curves. Basically, this requires holding the vane ten degrees off the wind tunnel centerline, releasing it without imparting any torque, recording its response on a strip chart recorder, and analyzing the results.

For the purpose of this evaluation, the method was applied to a number of different new wind vanes which were loaned to EPA by their manufacturers for these tests.

This report presents a short review of the theory of wind vane behavior and the test method, and an evaluation of the results.

2. Theory

Following the development of Wieringa (1967), the torque per unit angle on a wind vane which is at some angle β to the wind may be expressed as

$$\mathbf{N} = r\mathbf{F}/\beta, \tag{1}$$

where $\mathbf{N}$ is the torque per unit angle and r the distance from the pivot point of the vane to the center of effort of the force ($\mathbf{F}$) of the wind acting on the vane.

[1] On assignment from the National Oceanic and Atmospheric Administration.

[2] ASTM, 1980: Standard method for determining the dynamic performance of a wind vane. Draft No. 4, 3/11/80, ASTM, Philadelphia, Pa.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/J-81-340	Journal Article	PB82 127929

4. TITLE AND SUBTITLE	5. REPORT DATE
Measuring the Dynamic Performance of Wind Vanes	October 1981
	6. PERFOR OE 4 308092

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Peter L. Finkelstein	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Data Management and Analysis Division Environmental Monitoring Systems Laboratory U. S. Environmental Protection Agency Research Triangle Park, North Carolina 27711	A08A1D 11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Data Management and Analysis Division Environmental Monitoring Systems Laboratory U. S. Environmental Protection Agency Research Triangle Park, North Carolina	14. SPONSORING AGENCY CODE EPA 600/08

15. SUPPLEMENTARY NOTES
Published in Journal of Applied Meteorology, V.20 #5 May, 1981
pp 588-594

16. ABSTRACT

The American Society for Testing and Materials (ASTM) has proposed a standard method for testing the performance characteristics of a wind vane. This report presents the procedures used to test and evaluate the ASTM method, and the results of that evaluation. Twelve wind vanes were borrowed from their manufacturers and tested using the ASTM procedures. The theory of wind vane dynamics is briefly reviewed. Measurements of starting threshold, starting accuracy, delay distance, overshoot ratio, and damped wavelength were made. Damping ratio and natural wavelength were computed from the measurements. Based on the results of this test, it is concluded that the ASTM method provides a reasonable and reliable technique for determining performance characteristics for many wind vanes.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wind Direction Measurement Wind Vanes Meteorological Measurements Meteorological Quality Assurance	Meteorological Instrument Evaluation	43F 68A

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	7
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

As the vane moves in response to a change in wind direction, the center of force has a velocity $r\dot{\beta}$. Air resistance to the motion of the vane produces a force on the vane and causes the effective wind angle to change to β_v. It has been shown (Barthelt and Ruppersberg, 1957) that

$$\beta_v = \tan^{-1}\left(\frac{u\sin\beta + r\dot{\beta}}{u\cos\beta}\right) \tag{2}$$

$$\approx \beta + (r\dot{\beta}/u). \tag{3}$$

Assuming the small-angle simplification from Eq. (2) to Eq. (3) is valid, one may write for a vane with moment of inertia J, the equation of motion as

$$-J\ddot{\beta} = N\beta + (Nr/u)\dot{\beta}. \tag{4}$$

Let

$$d = Nr/u, \tag{5}$$

where d may be considered a damping force acting on the vane.

If N is a constant, Eq. (4) has two well-known solutions; one represents an overdamped or aperiodic return of the vane to equilibrium and the other represents a damped harmonic oscillation of the vane as it returns to equilibrium. Since most wind vanes are not overdamped, the solution to (4) is

$$\beta = \beta_0 \exp\left(\frac{-d}{2J}t - 2\pi i\,\frac{t}{t_d}\right), \tag{6}$$

where β_0 is an initial vane deflection at rest position, and

$$t_d = 2\pi\left[\left(\frac{N}{J}\right) - \left(\frac{d}{2J}\right)^2\right]^{-1/2}, \tag{7}$$

where t_d is the oscillation, or in this case, damped oscillation period of the vane.

The undamped, or natural period of the vane (t_0) is

$$t_0 = 2\pi(N/J)^{-1/2}, \tag{8}$$

while for critical damping the damping coefficient $d = d_0$ and

$$N/J = (d_0/2J)^2. \tag{9}$$

The damping ratio η is defined as the ratio of actual to critical damping coefficients, i.e.,

$$\eta = d/d_0. \tag{10}$$

Therefore

$$t_d = [2\pi/(N/J)^{1/2}](1 - d^2/4NJ)^{-1/2}, \tag{11}$$

or

$$t_d = t_0/(1 - \eta^2)^{1/2}. \tag{12}$$

The damped, or actual, wavelength of the vane (λ_d) may now be defined as

$$\lambda_d = ut_d = \lambda_0(1 - \eta^2)^{-1/2}. \tag{13}$$

At a maximum or minimum point on the curve of displacement versus time ($t = 0, t_d/2, t_d$, etc.), the oscillatory term is ± 1, so that

$$\beta = \beta_0 \exp(-dt/2J). \tag{14}$$

The overshoot ratio Ω is defined as the ratio of the amplitudes of two successive peaks,

$$\Omega = \beta_i/\beta_{i-1} = \exp[-(d/2J)(t_d/2)], \tag{15}$$

$$\Omega = \exp[-\pi\eta/(1 - \eta^2)^{1/2}]. \tag{16}$$

For Eq. (6) to hold, Eq. (4) must be an accurate description of the forces on the vane. Thus, the small angle assumption of Eq. (3) must be valid (hence, the 10 degree initial offset position), friction must be minimal, and the mean wind speed in the tunnel must be constant. The ASTM procedure will not be meaningful for vanes which do not meet these implied assumptions, or which do not behave as second order systems. For example, this procedure does not apply to a bivane with simultaneous initial deflections in both the horizontal and vertical planes.

With some systems which are well damped ($\eta > 0.5$), it may be difficult to measure the damped period for a full wavelength. Some authors (Wolkovitch *et al.*, 1962,[3] MacCready and Jex, 1964) have suggested measurement of the delay distance D to solve this problem. The delay time is defined as the time required for the vane to move from its offset position to 50% of its final equilibrium value. The delay distance, like the damped wavelength, should be invariant with wind speed (Moses, 1968), and is simply the delay time multiplied by the wind speed. MacCready and Jex (1964) have suggested the empirical relationship

$$\lambda_d = D(6.0 - 2.4\eta)/(1 - \eta^2)^{1/2}. \tag{17}$$

How well this approach fits the data will be examined in Section 4. Acheson (1970) has also suggested some alternative methods for measuring the response characteristics of vanes which have even larger damping ratios ($\eta > 0.7$). Since the vanes tested (and normally used) have damping ratios much less than that, the method was not evaluated.

3. Apparatus and procedure

A letter was sent to many major U.S. manufacturers of wind vanes describing the purposes of this test and requesting the loan of one or two models of the wind vanes they manufacture. A number of these companies indicated that they were interested in participating in the EPA/ASTM program, and subsequently sent vanes to EPA for testing. A list of the vanes which were tested under this program is given in Table 1.

[3] Wolkovitch, J. R., *et al.*, 1962: Performance criteria for linear constant coefficient systems with deterministic inputs. Systems Technology, Inc., for Aeronautical Systems Division, Wright-Patterson AFB, ASD-TR-61-501.

TABLE 1. List of wind vanes tested.

Name	Model
Bendix	Aerovane
Bendix	Wind Vane
Climet	12-15
Meteorology Research Inc.	1022
R. M. Young	Microvane
R. M. Young	Wind Vane
Weather Measure	102
Weather Measure	200
Weather Measure	204
Teledyne Geotech	53.2
Texas Electronics	2010

The procedures used to evaluate the starting speed, delay distance, and over-shoot of the wind vanes follow the ASTM method.

These tests were performed in a Kenney model 1391 wind tunnel located in the Fluid Modeling Facility, Division of Meteorology, Environmental Sciences Research Laboratory, EPA. The tunnel has a cross section of 1 meter square, with a 3 m test section length.

The ASTM method gives a procedure whereby several dynamic parameters of wind vane performance may be measured in a wind tunnel. These parameters, starting threshold, delay distance and overshoot, are defined as follows:

Starting threshold—the lowest wind speed at which a vane will turn to within 5° of the tunnel centerline from an initial displacement of 10°.

Delay distance (D)—the distance the air flows past a wind vane during the time it takes the vane to return to 50% of the initial displacement.

Overshoot ratio (Ω)—the ratio of the amplitudes of two successive deflections of a wind vane as it oscillates about the equilibrium position after release from an offset position.

The ASTM method requires that wind vanes be tested in a previously calibrated tunnel, with recording equipment which has a resolution of at least 0.5° and which will not distort the output signal.

Starting speed is measured by releasing the vanes from a 10° offset from the tunnel centerline with the speed of the tunnel set quite low. In this condition if the torque caused by the air is large enough, the vane will move toward the centerline of the tunnel. It will continue to move until the torque is no longer strong enough to overcome the dynamic friction. At this point the vane slowly comes to a stop. The starting threshold is the lowest air speed at which the vane will move from the 10° offset to within 5° of the tunnel centerline. This requirement must be met on 10 consecutive releases; five on each side of the centerline. The accuracy at starting speed is the mean of the absolute values of the angular positions at which the vane comes to rest at that starting speed.

Delay distance and overshoot are measured at 2, 5 and 10 m s^{-1} unless the starting speed of the vane is 1.75 m s^{-1} or greater, in which case only 5 and 10 m s^{-1} speeds are used. For these tests the vane is released from a 10° offset and, as with starting speed, the response is recorded. At each speed 10 tests are done; five on each side, and the results from each test averaged. Delay distance is obtained by measuring the time required for the vane to go from its offset position to a point halfway between the offset position and the point at which it initially crosses the final equilibrium position (tunnel centerline). The time, multiplied by the air speed in the tunnel, gives the delay distance.

Overshoot is measured on the same record used to compute a delay time. It is simply the ratio of the first peak displacement to the initial displacement. All ratios are averaged to arrive at the final overshoot ratio. This value may then be used to calculate the damping ratio.[4]

4. Results

While the ultimate goal of this study was to evaluate the ASTM methodology, this was difficult to do without collecting some data on individual vanes. Because this information may be of interest, it is presented in the following tables. Certain caveats should be kept in mind, however, while examining these results or comparing them with manufacturers specifications or other published results. One is that only one vane of each model was tested. While care was taken to eliminate faulty vanes, some of the ones tested may not have been representative of the entire model series. Another is that the ASTM method differs significantly from some other vane testing techniques, and the results should not be expected to be comparable.

Table 2 gives the manufacturers' names and model numbers of the vanes tested, the starting thresholds and accuracies, the delay distances, measured damped wave lengths, and overshoot and damping ratios. The precision figures given are for one standard deviation. The various vanes are given in alphabetical order by manufacturer. The starting threshold was measured in 0.1 m s^{-1} increments between 0 and 1.0 m s^{-1}, and 0.25 m s^{-1} increments above 1.0 m s^{-1}. A number of vanes were received for this program which were not tested either because the vane was damaged as received, or as in the case of the Electric Speed Indicator Co. model F420C-2 Wind Direction Transmitter, the design of the vane's electronics preclude its test by this procedure.

[4] Details on the equipment and procedure are given in Finkelstein, P., 1980: An evaluation of the ASTM standard method for determining the performance of a wind vane. EPA No. 600/4-80-028, 67 pp.

TABLE 2. Tabulation of wind vane test results.

Company	Model	Starting threshold (m s^{-1})	Starting accuracy (deg)	Delay distance (m)	Damped wavelength (m)	Overshoot ratio	Damping ratio
Bendix	Aerovane*	1.5	3.3 ± 0.19	2.0 ± 0.20	11.5 ± 0.40	0.49 ± 0.05	0.22
Bendix	Windvane	0.9	4.0 ± 0.34	1.0 ± 0.08	5.5 ± 0.22	0.33 ± 0.01	0.33
Climet	12–15	0.7	2.0 ± 0.58	0.65 ± 0.07	3.3 ± 0.21	0.28 ± 0.01	0.38
Meteorology Research Inc.	1022	0.4	2.2 ± 0.21	0.6 ± 0.08	3.4 ± 0.14	0.23 ± 0.02	0.43
R. M. Young	Microvane	0.5	2.9 ± 0.27	0.8 ± 0.11	4.8 ± 0.24	0.14 ± 0.03	0.53
R. M. Young	Windvane/6301	0.6**	2.8 ± 0.22	1.2 ± 0.10	7.2 ± 0.26	0.27 ± 0.05	0.39
Weather Measure	102*	2.5	1.8 ± 0.40	2.2 ± 0.14	10.6 ± 0.40	0.50 ± 0.06	0.21
Weather Measure	200*	2.25	2.7 ± 0.40	1.0 ± 0.07	4.6 ± 0.06	0.47 ± 0.02	0.23
Weather Measure	204	0.8	3.7 ± 0.45	1.1 ± 0.11	5.8 ± 0.11	0.48 ± 0.07	0.23
Teledyne Geotech	53.2	0.3***	1.7 ± 0.26	0.65 ± 0.08	2.6 ± 0.18	0.30 ± 0.04	0.36
Texas Electronics	2010	1.25	2.9 ± 0.50	1.2 ± 0.10	6.0 ± 0.20	0.29 ± 0.01	0.37

* For vanes with starting threshold 1.5 m s^{-1} or greater, tests of delay distance and overshoot at tunnel speeds of 2 m s^{-1} were not done. Results for these vanes are based on tests at 5 and 10 m s^{-1} only.

** A second test of the starting threshold of this vane done on a subsequent day showed a lower starting speed. The reason for this is not known. The first result is given in conformity with test procedures.

*** The starting threshold of this vane is probably less than 0.3 m s^{-1}, but the wind tunnel was not reliably calibrated below that speed, so no measurements could be made.

a. Starting threshold

Starting threshold and its corresponding starting accuracy are somewhat indeterminate numbers. They will depend on the size of the finite steps that are taken in doing the tests as well as the desired accuracy range. The lowest speed at which the first five tests on each side had a deflection of more than 5° was recorded as the starting threshold. It was not unusual to have several successful individual trials followed by one with a deflection of less than the required 5°. Under the procedure one would then adjust the tunnel to the next higher speed and try again. Since the final rest positions were somewhat random, however, it is not at all unlikely that five consecutive tests which were all successful could be done at the lower speed. On the other hand, if one wished to report a higher starting accuracy and was willing to sacrifice a lower starting threshold, the test could be commenced at a higher tunnel air speed. With this in mind, and considering that the accuracy with which the air speed in the tunnel is known at the lower range is on the order of 0.1 m s^{-1}, it is estimated that the accuracy of the threshold speed determination is within ±0.2 m s^{-1}.

Associated with each starting accuracy given in Table 2 is a one standard deviation precision value. The coefficient of variation for this measurement ($\bar{\sigma}/\overline{SA}$) is ~13%.

b. Average starting accuracy

Early drafts of the ASTM method specified that the absolute value of the accuracies from displacements to the left of the centerline and the right of the centerline were to be averaged, with this value representing the starting accuracy. Upon examining some preliminary results of this study, the ASTM committee noted that there was a distinct non-symmetrical distribution, or that the displacement on one side had a much lower degree of accuracy than did the other. An average of the values from the two sides then would give a misleadingly optimistic picture of the accuracy of the vane. The committee changed the method to require that the higher of the two average displacements (less accurate) be reported as the starting accuracy. Fig. 1 is a scatter plot of the new, or one-sided accuracy figures versus the old, or two-sided figures. As can be seen, for most vanes the change was not substantial, but for a few it was close to the maximum possible factor of two difference.

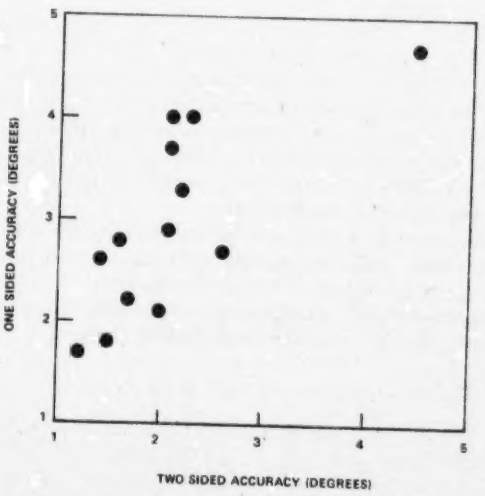

FIG. 1. Comparison of one-sided and two-sided starting accuracy.

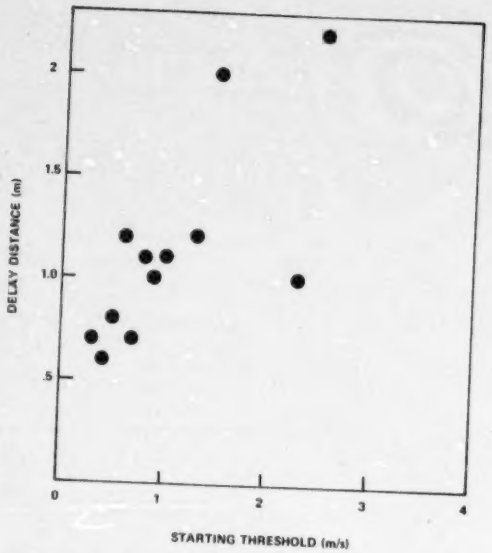

FIG. 2. Comparison of starting threshold and delay distance.

c. *Overshoot and damping ratios*

Overshoot ratios ranged from 0.14 to 0.49, with a mean of 0.34. The average standard deviation of the overshoot measurements for each instrument ranged from 0.008 to 0.07, with a mean value of 0.032 for all instruments. The coefficient of variation for this measurement is 9.9%. Thus 10% would be a good estimate of the precision of the overshoot measurements. Since the damping ratio η is roughly inversely proportional to overshoot ratio, 10% is also a reasonable estimate for its precision.

d. *Delay distance*

Delay distances measured in this study ranged from 0.6 to 2.2 m, with a mean of 1.12 m. The standard deviation of the delay distance measurements for each instrument ranged from 0.07 to 0.2 m, with a mean value of 0.1 m for all instruments. The average coefficient of variation was 9.6%, thus implying that 10% is also a reasonable expectation for the precision of this measurement.

In general, vanes with higher starting thresholds had longer delay distances. This can be seen in the scatter plot of Fig. 2. Its usefulness may be limited, but in principal one could design a vane with a long delay distance and a low starting threshold.

e. *Damped wavelength*

The damped wavelength λ_d measured in this study ranged from 2.6 to 11.5 m, with a mean of 5.94 m. The average of the standard deviations for all instruments was 0.22 m, with an average coefficient of variation of 3.9%. One could thus reasonably expect a precision of ~5% for this measurement.

Comparing this with 10% precision for the delay distance measurement, it would seem that the damped wavelength would be the more precise of the two measurements to take. However, it should be realized that for vanes with large damping ratios (0.5 or greater), the second peak may be very difficult to define, and for these vanes, delay distance measurements may be much more precise. In actual practice, either may be easily measured, and as shown below, the relationships between the two is consistently reliable.

Eq. (16) gives a relationship between delay distance, damping ratio, and damped wave length. A comparison of calculated λ_d, using the measured delay distance and damping ratio, and measured λ_d is shown in Fig. 3. As can be seen the agreement is quite good. The line of best fit has a slope of 1.015 and an intercept of 0.21. The standard error of estimate ($S_{y\cdot x}$) is 0.71 and the correlation coefficient is 0.97 (using calculated λ_d as the dependent variable).

Eq. (17) can be rewritten as

$$\lambda_d = kD, \tag{18}$$

where

$$k = (6 - 2.4\eta)/(1 - \eta^2)^{1/2}.$$

For η between 0.2 and 0.5 (the range of all vanes tested), k varies between 5.5 and 5.6.

The observed relationship between delay distance and measured λ_D is shown in Fig. 4. As can be seen, the assumption of a straight line fit is reasonable. The

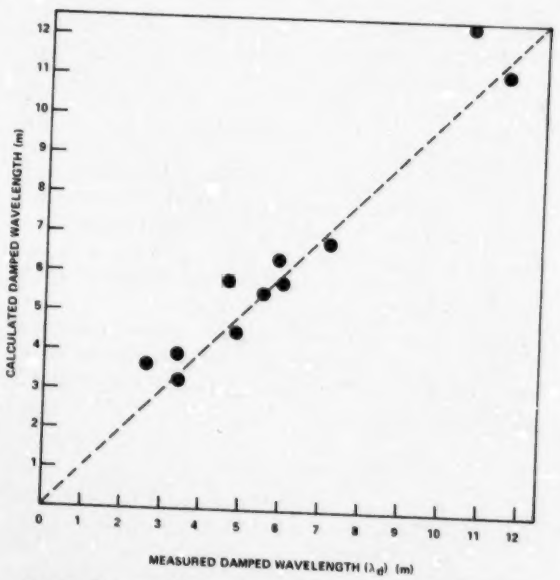

FIG. 3. Calculated versus measured damped wavelength.

linear regression best fit for the line is

$$\lambda_d = 5.27D + 0.06, \quad (19)$$

with $S_{y \cdot x} = 0.64$ and the correlation coefficient equal to 0.97.

There would seem to be little justification in the data for preferring one form of the relationship over the other so the choice is left up to the user.

f. Offset angle

The ASTM method requires an offset angle or displacement of 10° from the tunnel centerline. In the past other angles have been used by various manufacturers and others studying vane response. The author was able to do a very limited comparison of the effects of various offset angles on the response of one vane, the Texas Electronics 2010. The results of the tests are given in Table 3.

The results confirm that the test results are dependent on offset angle. All the vane parameters showed significant differences. Not surprisingly, the starting threshold decreased (or the accuracy increased) with increasing offset angle.

The delay distance also increased with increased offset angle. Since the delay distance is in a sense the length of an air column needed to move the vane from one position halfway to a new one, and since that distance is increasing with increasing offset angle, the increase in delay distance may also be an understandable event. One should note, however, that theoretically the natural and damped wavelengths are not functions of offset angle.

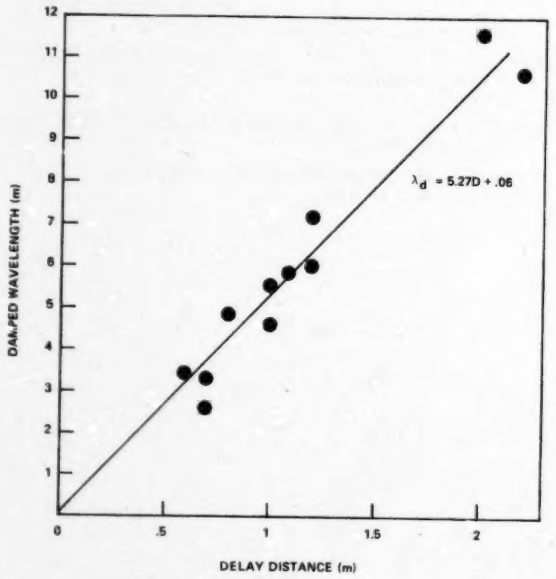

FIG. 4. Measured damped wavelength versus delay distance.

TABLE 3. Comparison of vane parameters for offsets of 10, 15 and 20° measured on the Texas Electronics 2010 vane (parameters for this test were measured at 2 and 5 m s^{-1} only).

	10°	15°	20°
Starting threshold ($m\ s^{-1}$)	1.25	1	1
Accuracy (deg)	2.9 ± 0.5	2.1 ± 0.8	1.6 ± 0.7
Delay distance (m)	1.2 ± 0.1	1.3 ± 0.1	1.5 ± 0.1
Overshoot	0.26 ± 0.02	0.28 ± 0.01	0.27 ± 0.02
Damping ratio	0.39	0.37	0.38

Overshoot also changed with offset angle, although not in any obviously systematic way. While the difference between the offsets at 10° and 15° is statistically significant, the results may still be an artifact of the small sample size or experimental error. This could be resolved with a more thorough study.

5. Conclusions and recommendations

The basic conclusion of this study is that the ASTM draft *Standard Method for Determining the Dynamic Performance of a Wind Vane* does provide a reasonable and reliable technique for determining standard performance characteristics for many commercially available wind vanes. The method also provides good standard definitions for many terms which have been used with some ambiguity in the past.

Using reasonable care, most laboratories with proper facilities should be able to measure performance characteristics of many of the wind vanes on the market today. For those vanes which were not testable, modifications which do not affect dynamic performance may be possible, so that organizations with interest in them will be able to evaluate these vanes.

Because of the facilities required, it is not reasonable to expect that many of the users of wind vanes will be able to test their own equipment. If the manufacturers and various independent testing laboratories adopt the ASTM method, vanes could be certified to meet specified performance criteria and could be returned to the manufacturer or other laboratory for recertification should it become necessary. A reliable program of this type should take much of the guesswork that is now necessary out of the evaluation of meteorological data.

The general subject of delay distance and its relationship to damped wavelength, damping ratio, and offset angle has not been adequately resolved. Theoretical relationships to replace the present empirical ones, plus a more thorough experimental program would be needed to attack this problem.

The variability of results is a major area of uncertainty. This includes variability between similar models, variability with age, and variability of results measured at different laboratories. Variability between similar models should be addressed in order

to determine whether all vanes of a similar design need to be tested, or whether representative sampling will be adequate.

Variability between laboratories would be easily addressed by an interlaboratory comparison test. Such a test is being planned by members of the ASTM Meteorological Measurements subcommittee.

The question of variability with age could also be addressed in a straightforward test. It would be interesting to see if changes in the various parameters could be related directly to bearing wear, so that simple measurements of torque could be substituted for the wind tunnel tests on older vanes as a method of field calibration. Answers to these questions and reliable performance specification may help improve our understanding of the data we have been receiving from this elegantly simple meteorological instrument.

Acknowledgments. This work was done with the aid and cooperation of many people and organizations. We are most grateful to the companies that loaned us the wind vanes that were used: Bendix Co., Environmental Science Division; Climet Instruments Company; Electric Speed Indicator Co.; Meteorology Research Inc.; R. M. Young Company; Teledyne Geotech; Texas Electronics Inc., and Weather Measure Corporation. The support of EPA's Fluid Modeling Facility was essential, and I wish to thank its director, Dr. William H. Snyder, and members of the very capable staff, Milton Fabert, Robert E. Lawson, Myron Manning, Michael Shipman, and Roger S. Thompson, for their generous help and many kindnesses. Finally and most especially I would like to thank Ms. Kathy Brehme (now Lieutenant, USAF) for her many hours of excellent assistance collecting and reducing the data for this project.

APPENDIX

List of Symbols

d	aerodynamic damping
d_0	critical damping
D	delay distance
$\mathbf{F}$	force of wind on vane
J	moment of inertia of vane
$\mathbf{N}$	torque per unit angle of wind on vane
r	distance between pivot and center of mass of vane
t	time
t_d	damped period of vane
t_0	natural period of vane
t_1	delay time
$\mathbf{u}$	wind velocity
u'	turbulent fluctuation of wind speed
β	angle between vane and wind
β_0	initial offset angle
β_v	effective angle of attack
$\dot{\beta}$	$d\beta/dt$
$\ddot{\beta}$	$d\dot{\beta}/dt$
η	damping ratio
λ_d	damped wavelength
λ_0	natural wavelength
σ	standard deviation
Ω	overshoot ratio

REFERENCES

Acheson, D. T., 1970: Response of cup and propeller ratios and wind direction vanes to turbulent wind fields. *Meteor. Monogr.*, No. 33, Amer. Meteor. Soc., 252–261.

Barthelt, H. P., and G. H. Ruppersberg, 1957: Die mechanesche Wind fahne, eine theoretiscke und experimientelle Untersuchung. I. *Beitr. Phys. Atmos.*, **29**, 154–185.

Camp, D. W. and R. E. Turner, 1970: Response tests of cup, vane, and propeller wind sensors. *J. Geophys. Res.*, **75**, 5265–5270.

MacCready, P. B., Jr., and H. R. Jex, 1964: Response characteristics and meteorological utilization of propeller and vane wind sensors. *J. Appl. Meteor.*, **3**, 182–193.

MacCready, P. B., Jr., 1965: Dynamic response characteristics of meteorological sensors. *Bull. Amer. Meteor. Soc.*, **46**, 533–538.

Moses, H., 1967: *Meteorology and Atomic Energy*. AEC, Oak Ridge, TN, 257–308.

Wieringa, J., 1967: Evaluation and design of wind vanes. *J. Appl. Meteor.*, **6**, 1114–1122.